NACA TN 2271

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2271

FURTHER STUDY OF METAL TRANSFER BETWEEN SLIDING SURFACES

By J. T. Burwell and C. D. Strang

Massachusetts Institute of Technology

NACA

Washington

January 1951

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SUMMARY

This is a report of the continuation of research begun by Sakmann, Grossman, and Irvine (NACA TN 1355) to determine what role, if any, is played by the transfer of metal from one rubbing surface to the other in the formation of the characteristic surface coatings on certain piston-ring materials during run-in in an aircraft engine. For the detection of this transfer the technique originally developed in the Lubrication Laboratory at the Massachusetts Institute of Technology for measuring extremely small amounts of transferred material was employed. It consists of making one of the two rubbing surfaces radioactive, carrying out the friction test, and then examining the other surface for signs of radioactivity. The materials examined consisted of nitralloy steel, both nitrided and unnitrided, and several different types of chromium-plated surfaces. In addition, the transfer to actual piston rings, both new and used (after running), was investigated. The effects on transfer of load, speed, distance of travel, repeated travel over the same path, hardness of the moving surface, and type of chromium plate were studied.

From the results of the tests it could be surmised that, under the conditions of running in an aircraft-engine cylinder, a certain amount of nitrided steel from the cylinder barrel will probably be transferred to the surfaces of nitrided-steel, cast-iron, or chromium-plated rings. Such transferred material may, therefore, be a factor in the formation of the characteristic surface layer often observed on such rings. This strengthens the suggestion made in the previous work that a possible pretreatment to obtain a desirable surface layer might consist of running rings in a special cylinder having walls of selected composition and controlled hardness to give surface coatings of highly improved characteristics in a minimum length of time.

INTRODUCTION

This work is the continuation of research begun by Sakmann, Grossman, and Irvine (reference 1, denoted hereinafter as part I) to study one aspect of the running-in and wear of certain piston-ring and cylinder

materials, namely, the transfer of metal between the two when running together as in an engine. It had been observed previously by other workers (references 2, 3, and 4) at the Lewis Flight Propulsion Laboratory of the NACA that the running of piston rings, particularly nitrided ones, in nitrided cylinder barrels induced the formation on the ring of a surface coating which had different, and in some respects superior, properties compared with those of the bulk ring material. It was the purpose of the present research to see to what extent these rubbing conditions could have produced transfer of metal from the barrel to the ring, which transfer could then have played a part in the formation of this coating. Therefore, as regards materials, the present work has concerned itself with the transfer between nitrided steel of various hardnesses and also between chromium plate and nitrided steel.

The present investigation is in two parts. The first studies the transfer between small cylindrical friction specimens made of nitralloy and of chromium plate. The second part studies the transfer from such a specimen to actual aircraft-engine piston rings made of nitralloy, both new and used by having been run in an engine. This was to show whether the run-in layer on such rings, once formed, was more or less susceptible to further metal pickup from the engine barrel.

To measure the amount of transfer, use was made of a technique originally developed in the Lubrication Laboratory at the Massachusetts Institute of Technology (reference 5). Briefly, it consists of making one of the two rubbing surfaces radioactive, carrying out the prescribed rubbing schedule, and then examining the other surfaces for signs of radioactivity. The method has the advantages of (1) extreme sensitivity and (2) detection of transfer between surfaces of the same chemical composition.

PREPARATION OF SPECIMENS

Method of Activation

The original work employing this radioactive tracer technique (reference 5) activated one of the rubbing surfaces by exposing it to a beam of deuterons from a cyclotron. By this method a high concentration of activity is produced near the surface, but the concentration decreases sharply with depth owing to the low penetrating power of the beam of charged particles. The high surface concentration makes for high qualitative sensitivity with a minimum of hazard in handling, but the steep concentration gradient makes it very difficult to calibrate the transferred activity quantitatively in terms of weight of metal. It was because of the latter difficulty that in part I (reference 1) of the present research the activation of the friction specimen was accomplished by adding radioactive manganese to a small melt of the steel and then from this steel fabricating a small button that served as the stationary friction rider. This procedure achieved a uniform distribution of activity throughout the friction-specimen material so that quantitative calibration was much improved. However, since the procedure involved a complete series of steel-making, fabricating, and heat-treating operations on a total mass of steel of only a few grams, the whole process was very laborious and costly for the amount of data that could be obtained. Furthermore, there was no assurance that the properties of the friction specimen so produced, particularly the surface finish, could be controlled or would be typical of actual piston rings and cylinders.

For the above reasons a third method of activation has been used in the present work. It consists of preparing the friction specimen in its final form, then having it irradiated in the slow neutron pile at Oak Ridge, Tennessee, operated under the auspices of the U. S. Atomic Energy Commission, and finally having it returned to this laboratory for the friction experiments. The length of time of irradiation was 1 to 2 months. The ambient neutron flux was not known.

Two specimens were irradiated. One was made of nitrided steel (Nitralloy 135 Modified), and the other of chromium plate. The nominal composition of the nitralloy was as follows:

Carbon	0.38 – 0.45 percent
Manganese	0.40 – 0.70 percent
Silicon	0.20 – 0.40 percent
Chromium	1.40 – 1.80 percent
Aluminum	0.85 – 1.20 percent
Molybdenum	0.30 – 0.45 percent
Iron	Remainder

On exposure of the preceding elements to neutrons, manganese (Mn^{56}), molybdenum (Mo^{98}), and aluminum (Al^{28}) give high specific activity (percentage of radioactive atoms per unit weight), but have too short half lives to be practically useful. Carbon (C^{14}) in such small concentration does not yield enough activity with this length of exposure; silicon (Si^{31}) has too small specific activity and' in addition gives off no gamma rays or X-rays. This leaves iron and chromium. Among their various isotopes the following reactions with neutrons are of importance:

$$Fe^{54} + n^1 \longrightarrow Fe^{55}$$

$$Fe^{58} + n^1 \longrightarrow Fe^{59}$$

$$Cr^{50} + n^1 \longrightarrow Cr^{51}$$
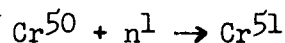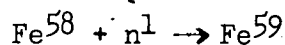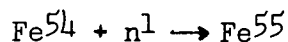
Iron (Fe^{55}) has a half life of about 4 years and decays solely by K-electron capture; this means that it emits the characteristic X-rays of manganese (5.9 kev). Iron (Fe^{59}) has a half life of 47 days and decays with the emission of beta rays of 0.26- and 0.46-mev energies and gamma rays of 1.10 and 1.30 mev (reference 6). Chromium (Cr^{51}) also decays by K-electron capture emitting 5.0-kev X-rays together with a few weak gamma rays (reference 7). The specific activity of the chromium is many times greater than that of both the active isotopes in the iron combined - so much so in fact that in the nitralloy the chromium contributed about one-third of the total activity observable with the detection system used.

Friction Specimens

The surfaces whose transfer properties were to be studied were of three kinds, namely, nitralloy friction specimens, chromium-plated friction specimens, and aircraft-engine piston rings. They are described below:

(a) The standard nitralloy friction specimens, both moving and stationary, consisted of nitralloy cylinders of 3/4-inch diameter, $2\frac{15}{16}$-inch length and with approximately 1/16-inch wall thickness. (The one specimen that was activated was reduced in wall thickness to 1/32 inch in order to decrease the total weight of active material and hence the danger in handling.) The nitralloy was Nitralloy 135 Modified, whose composition is given above.

The specimens were made up to size, nitrided for 48 hours at 975° F following standard practice (reference 8), and then were ground to varying depths to give varying degrees of hardness, depending on the depth of nitrided case removed. In all cases the white layer was removed. The surface hardness was measured with the Rockwell Superficial Hardness Tester, using the 15-N scale. The surface roughness was measured by means of an Abbot Profilometer. The data on the surface hardness and surface roughness are given in table I.

(b) The standard chromium-plated specimens were of four different types:

(1) A thick chromium plate (about 0.005 in.) was plated directly on cylinders of the standard dimensions and made of a low-carbon steel. The plating conditions were a current density of 2 amperes per square inch at 50° C. This is so-called "hard chrome" plate and was used in the as-plated condition. Under the microscope it has a distinctly nodular appearance, as shown in figure 1.

(2) A thick chromium plate (about 0.005 in.) was plated, using the same conditions, directly on the heads of short steel studs which had previously been ground to a cylindrical shape with 3/8-inch radius of curvature. The appearance of the surface was similar to that shown in figure 1. These were only used as stationary specimens. (This will be referred to in this report as "nodular" because that describes its microscopic appearance. However, this is not what is referred to in the plating industry as "nodular" but rather as thick "hard chrome.")

(3) Chromium-plated cylinders, prepared as under item (1) above, were carefully superfinished. This gave an extremely smooth surface.

(4) Steel cylinders of the standard dimensions were given a porous chrome plate following present commercial practice. This type of plate gives a surface texture consisting of fairly flat areas interrupted by depressions or voids. A photomicrograph of it is shown in figure 2.

The roughnesses of the chromium specimens are also given in table I. In view of the thinness of the plating even a Rockwell superficial hardness would not have much significance and it was not possible to measure a Knoop hardness. However, from the plating conditions and the data given by Brenner, Burkhead, and Jennings (reference 9), one could estimate its Knoop hardness as about 900 or 94 on the Rockwell 15-N scale. This should be the hardness of the plated specimens (1), (2), and (3) above. As the plating conditions for the porous chromium plate were not known, no estimate could be made of its hardness.

.(c) The new and used aircraft-engine piston rings were furnished by the NACA. They were used as received except for surface cleaning. Their characteristics are given in the last section under Results in this report.

One nitralloy specimen and several chromium-plated studs were sent to Oak Ridge for neutron irradiation. The nitralloy specimen was irradiated for 2 months, while the studs were irradiated for 1 month - not necessarily at the same neutron flux.

FRICTION APPARATUS

The principle of the present friction apparatus follows, in general, that employed in part I but has the additional feature of measuring the instantaneous friction force which was not possible in the previous work. Essentially it consists of a fixture, carrying the stationary friction specimen, which is mounted in the tool holder of a simple bench lathe so that use is made of the lathe spindle to rotate the moving specimen. The two cylindrical specimens are rubbed with their axes at right angles, thus providing a concentrated area of contact.

The apparatus is shown diagrammatically in figure 3. There is a rigid upright bar, mounted in the tool post of the lathe, at the top of which is pivoted a horizontal member. To this member is pivoted a rigid vertical member having a yoke at its lower end in which the stationary . specimen is held on a removable mandrel. The load between the two specimens is supplied by the weight suspended from the end of the horizontal member. A counterweight at the other end of this member counterbalances all of the assembly except the loading weight. The motion of the yoke carrying the stationary specimen is restrained by a strain ring, attached to the upright, on which are mounted four strain gages. Vibration of the yoke induced by stick-slip friction phenomena between the rubbing specimens is damped by means of a dashpot. The friction force produced by rotation of the moving specimen compresses the strain ring and is measured by the strain gages mounted thereon. The end of the yoke is free to slide on the surface of the ring so that its purely vertical motion will not produce any deflection of the gages. This was checked experimentally.

The strain gages form the arms of a Wheatstone bridge connected so that their resistance changes due to deflection add, thus increasing the sensitivity, as shown in figure 4. On the other hand, the changes due to temperature and shearing forces on the ring cancel. The bridge is balanced by means of a calibrated slide-wire, using a Leeds and Northrup type P galvanometer as the null instrument. There is a resistance in series with the galvanometer which can be shorted out by means of a toggle switch to increase the sensitivity. There is also an

additional variable resistance with which to set the zero, and both it
and the slide-wire are shunted for greater sensitivity.

MEASUREMENT OF ACTIVITY

Means of Detection

Two means of detection of radioactivity are employed in this work,
a Geiger-Müller counter and autoradiography. The former gives a quan-
titative measure of the material transferred, while the latter gives
supplementary qualitative information about its distribution.

Since the majority of the radiations from the isotopes of interest
in this work were beta rays and soft X-rays, the counter employed was
a standard commercial beta-ray model, of the Scott type, filled with
argon to a pressure of 10 to 15 centimeters and having a mica window
thickness of 2.2 milligrams per square centimeter. The scaler used in
conjunction with this counter was of standard design with a scale of 128
and a mechanical register. The counting tube and sample to be counted
were housed in an aluminum-lined lead shield of $1\frac{1}{4}$-inch wall thickness.
The sample is supported on a tray which can be located exactly at one
of five different distances from the counter window. The background
counting rate of this system was about 25 counts per minute. The counter
was not used on the piston rings owing to their awkward geometry and low
concentration of transferred material.

The autoradiography of friction tracks was first employed by Gregory
(reference 10) and consists of pressing a photographic film tightly
against the friction track and allowing the track to take its own picture.
In the present work it was used on both the friction specimens and the
piston rings. In the case of the former, the film is wrapped around the
inert specimen on which the tracks are located and is pressed into
intimate contact with it by means of a layer of sponge rubber held around
it by rubber bands. The intimate contact is necessary to avoid blurring
and thus obtain a sharp picture. In the case of the piston rings, they
were inserted inside a short steel cylinder, whose diameter was approxi-
mately that of the engine cylinder bore, with the photographic film
between the rings and the wall of the steel cylinder. The ring pressure
insured intimate contact. More than one ring can be inserted and exposed
at one time to a single film. This facilitates quantitative comparison
between different rings.

Standard Eastman no-screen X-ray film was used with exposure times
of from 24 to 48 hours and was developed in X-ray developer in the usual

way. In spite of its coarse grain size the X-ray film appeared to have sufficient resolution to show the details of the friction track. A special high-resolution spectroscopic film (Eastman Type 649-G4) was tried but was so slow that the exposure times became inconveniently long.

Preparation for Radiation Counting

One of the most difficult and troublesome steps in the present experiments has been the quantitative measurement, by means of the Geiger counter, of activity picked up on the inert specimen and its conversion to weight of transferred radioactive material. In the previous work the radioactive manganese had a fairly intense gamma radiation which rendered it easy to measure without much regard to geometry or physical state. However, in the present case the very low energies of the radiations involved required care in the preparation of the specimen for activity measurement if reasonable sensitivity and reproducibility were to be achieved.

As is evident from the geometry of the friction apparatus, the friction track on the moving surface lies in a circular path around the cylinder. A relative measure of the activity along a portion of the track can be obtained by placing the friction specimen near the Geiger-Müller counter and observing the resulting counting rate. For these radiations the specimen itself is strongly absorbent of the radiation from the part of the track on the side away from the counter. However, by rotating the specimen to three or four different positions the entire track can be surveyed and an average figure for the counting rate for this particular geometry can be obtained, provided the distribution of activity along the track is fairly uniform. If all the friction specimens are the same size and shape relative values for the transfer can be obtained among them which will show trends with load, speed, hardness, and so forth. This was the method used to obtain the relative values of transfer in all the friction experiments reported here. This procedure assumes that the transferred material on the track is not thick enough to have appreciable self-absorption.

To convert these data to absolute weights of material transferred turns out to be more difficult. To obtain such a conversion a known weight of the active material must be disposed in the same geometry with respect to the counter as the unknown sample so that counting rates from the two may be directly compared. The counting rate is particularly sensitive to geometry when the energy of the radiation is low, as it is in this case. Since the geometry of the circular track on the friction specimen would be difficult to reproduce, it was necessary to remove all of the material from the track including a safe margin of base metal in

the vicinity and redistribute it in some simple geometry, such as a thin circular layer of uniform thickness. A small known weight of material taken from the active specimen is distributed in the same shape and the counting rates from the two are compared at as nearly the same time as possible. By comparing the counting rates at the same time the effects of radioactive decay and variations in counting rate of the counter are eliminated.

A quantitative plating procedure for distributing radioactive iron in a thin uniform circular area has been worked out by Peacock and associates (reference 6). However, this method cannot be applied to alloys of iron and chromium or to pure chromium since there is no known method of plating chromium quantitatively from solution. Therefore alternative methods had to be sought.

Even the smallest chips removed mechanically from the friction track gave such large and variable self-absorption of their own emitted radiation when placed directly under the counter that this method could not be used. Evaporation to dryness of an acid solution of the metal was better but the results were still quite variable owing to the tendency for the residue to deposit in little lumps rather than in a thin uniform layer. Concentration in a fixed volume and shape of solution was very ineffective because of the high absorption of the radiation by the liquid. Even a specially designed immersion counter did not improve this appreciably.

Of all the methods tried, a precipitation procedure was found to be the most satisfactory and was finally employed. Essentially it consisted of precipitating the hydroxides of iron and chromium from the acid solution in which the metal had been dissolved and then filtering them in a special glass apparatus onto a flat piece of hard filter paper in a circular area of uniform thickness. The specially designed filtering apparatus which makes this method possible has been produced by the Tracerlab Company of Boston. It consists of a fritted glass disk fused flush into the top of a glass funnel. Filter paper is placed flat on the disk and a straight-walled glass tube, one end of which is ground flat, rests snugly on top of the filter paper without leaking. The two parts are held tightly together by wire springs.

The details of the procedure for removing the transferred material from the friction track on the inert specimen and precipitating it in a thin uniform circular area are as follows: First, the activity of the track on the specimens is counted directly in the Geiger counter. Then all of the specimen, except a circumferential band about 1/4 inch wide in the center of which is the friction track, is painted with a protective stripping lacquer. A convenient one is Tempro-Tec made by the United States Stoneware Co. Then the cylindrical specimen is etched in 30 milliliters of one-tenth normal sulfuric acid. After the etching

the track area on the specimen is counted in the Geiger counter again to
be sure that all the active material has been removed. This solution is
boiled down to about 20 milliliters to which 1 milliliter of saturated
bromine water is added, the solution is mixed for about 1 minute, and
the excess is boiled off. Then 1 or 2 drops of concentrated ammonium
hydroxide is added until the pH is about 8. The solution is kept hot and
stirred for about 1 minute; then the precipitate is allowed to settle for
10 minutes. This brings down all the iron and chromium as insoluble
hydroxides. It is then filtered and washed, and the washings are
refiltered. The filter paper is removed, allowed to dry for about 1 hour
on a low-temperature hot plate, and then covered with 2 or 3 drops of a
polystyrene base coil dope (liquid "912" made by American Phenolic
Corporation) diluted about 35 to 1 with "916" thinner. The filter paper
is then counted in the Geiger counter. By this means an equivalence is
obtained between the number of counts of the transferred material while
on the friction specimen to the number of counts of the same active
material when precipitated on the filter paper. As an example a friction
track which gave 12.4 counts per minute (net) when counted on the fric-
tion specimen gave 25.8 counts per minute (net) when counted on the filter
paper. This gave a ratio of the latter to the former of approximately 2.0
for the radioactive nitralloy which was used in the subsequent calculations.

Representative friction tracks produced by the chromium were also
counted on the friction specimen and then removed, precipitated on filter
paper, and counted again to complete the quantitative calibration of
chromium since this ratio for the chromium may not necessarily be the
same as for the nitralloy. In this case, the track can be most con-
veniently removed by electrolytic etching, using a basic solution con-
sisting of 2.5-percent sodium hydroxide instead of the acid solution.
This does not attack the steel of the inert specimen carrying the track
and is convenient as it does not clutter up the precipitation step with
a large mass of inactive iron. With this etch the chromium is dissolved
as chromate. The current density used was approximately 1.0 ampere
per square inch, the specimen having been painted with stripping lacquer
as before, leaving a circular band 1/4 inch wide exposed. The ratio of
the counting rate of the chromium track material when precipitated on
filter paper to the counting rate when on the specimen was found to be
approximately 1.5.

Calibration of Radioactive Standards

A calibration standard for the nitralloy was prepared by dissolving
a weighed chip from the radioactive specimen in dilute hydrochloric acid
and diluting to a convenient volume such as 1 to 4 milligrams of alloy
per milliliter. A measured volume of this solution was then carried
through the precipitation procedure described above for the nitralloy
friction track and counted as a precipitate on filter paper. An

average obtained from doing this a number of times gave an equivalent
of 27.0 counts per minute per microgram at 9 weeks after irradiation,
which is when most of the track counts were taken. Using the ratio
of 2 derived above, this means that 1 count per minute (net) from a
friction track on the specimen at that time was equivalent to
0.074 microgram of transferred active material. This gives the required
calibration for transferred nitralloy.

    As regards making a standard solution of the plated chromium, it
was not convenient to remove mechanically a chip of the chromium plate
alone from the stud without removing some of the steel substrate also.
This steel has a certain amount of activity of its own but, as it does
not enter into the transfer, its presence would only upset the calibra-
tion. Hence the basic electrolytic etch described above was again very
convenient for removing the chromium plate without the steel of the
stud, only here the current density was nearer 10 amperes per square inch.
The weight of chromium removed could be determined either by loss in
weight of the stud or by colorimetric analysis of the solution. The
latter method was used and is as follows: 10 cubic centimeters of the
resulting solution was diluted to about 200 milliliters, 2 grams of
ammonium bifluoride was added to eliminate any iron, and 15 milliliters
of concentrated hydrochloric acid was added and 10 milliliters of potas-
sium iodide solution. This solution was titrated with standard one-
normal sodium thiosulfate until the brown color formed from the iodine
turned to straw color. Then 3 milliliters of starch solution were added.
The previously untitrated iodine caused a deep blue color with the starch.
This was again titrated until a colorless solution resulted. By this
means the concentration of chromium in the etching solution was deter-
mined and is probably more accurate than in the loss-of-weight method.
A volume of this solution containing 0.024 milligram of chromium to
which was added a solution containing 1.0 milligram of inactive chromium
as carrier was acidified, and 1 milliliter of 3-percent hydrogen peroxide
was added to reduce the chromate to a chromic solution. The excess
hydrogen peroxide was boiled off and the same procedure as described
above was used to precipitate and filter. Two such standards were pre-
pared and counted every 4 or 5 days during the course of the experiments.
Their rate of decay agreed fairly well with the reported half life of
27 days for chromium (Cr^{51}). Their specific activity about 7 weeks after
irradiation was 86.7 counts per minute per microgram of chromium.

EXPERIMENTAL PROCEDURE

    In making the rubbing transfer runs the question of what lubrica-
tion to use arose. To simulate the lubrication conditions in a firing
aircraft engine, that is, the combustion process, exhaust gases, variable

oil supply, and variable speed throughout the stroke, would be exceedingly difficult. On the other hand, to use the normal aircraft lubricant under the relatively cool, steady-speed conditions of the experimental friction apparatus would hardly be representative of actual engine conditions. It would in fact be much too mild so that absence of transfer would not be indicative of its absence in the engine. It was finally decided to run the rubbing experiments dry since that is probably the condition of actual operation at the top of the piston stroke where most of the run-in and scuffing is thought to occur. Even if there is a little lubricant present at the top of the stroke in the engine it is somewhat counter-balanced by the absence of heat in the present test conditions.

Since the tests were therefore to be run "dry," that is, no lubricant purposely added, the problem of cleaning the friction specimens arose. The principal adventitious lubricants encountered will be grease from the air, water vapor, and oxide films. As already stated, all the nitralloy specimens were finish-ground and were free of visible rust when used. Just before the friction run, the inactive specimens were cleaned both with benzene and with sodium hydroxide solution using vigorous rubbing until water would spread evenly over them. Since the active specimen had to be handled at a distance of 14 inches it was merely swabbed with a paper towel dipped in the cleaning liquid and held in a pair of tongs. Extreme initial cleanliness of the stationary specimen, which was always the active one in these experiments, is not so important, as the running will wear the stationary spot clean of all contamination in a very few revolutions of the rotating specimen and all runs were much longer than this.

After cleaning, the inactive specimen was mounted on an expanding mandrel which was in turn mounted between the head and tailstock of the lathe and rotated by means of a dog. The active specimen was mounted on another mandrel, between centering cones, which was in turn mounted in the stationary yoke. After each run it was rotated on its mandrel so as to bring a fresh area to bear on the moving member. The appropriate weights were loaded on the tray and the horizontal arm of the friction apparatus was raised by means of a cord until the run was ready to begin. At the end of the run the bar was again lifted. Thus the moving specimen was always running at full speed when the specimens were in contact.

In the case of the piston rings a fixture was made which held them clamped with the gaps closed but left the entire ring face free. The fixture was rotated by the lathe spindle and the stationary specimen rode on the face of the ring, the axes of the two being at right angles as before. The vertical member of the friction apparatus can be extended to accommodate various diameters of rotating specimens.

The safety distance of a radioactive body is the distance at which a person would receive a radiation dosage of 0.1 roentgen during a 10-hour day. A dosage of 0.1 roentgen per day can be tolerated by humans indefinitely and is considered safe. The safety distance for the active nitralloy specimen was 14 inches and for the chromium-plated stud was 6 inches. Hence the cleaning of the specimens, the mounting of them in the friction apparatus, and the making of the friction runs all had to be carried out at a distance. This necessitated developing certain specialized tools in addition to ordinary tongs for handling the specimens. A simple procedure had also to be formalized by experience.

RESULTS

Transfer to Friction Specimens

The first results obtained showed that under most conditions some transfer of material between the rubbing specimens would take place. This confirmed the findings of part I. It was then of interest to see how the amount of transfer varied with the operating conditions. This had not been done in the previous work. It was also of interest to see how the transfer varied with the hardness of the friction specimens and whether there was any correlation between transfer and friction coefficient. The results are summarized in tables II to VIII and figures 5 to 8. Results from part I are included where pertinent, the hardness values being converted from Knoop to Rockwell 15-N and the distance of travel corrected as described below.

Table II gives the results of several runs showing the friction coefficient and the amount of metal transferred between two hardened nitralloy specimens run for 1 minute at a relative surface speed of 73 feet per minute under various loads. An autoradiograph of these runs, which were all made on the same rotating specimen, is shown in figure 5.

Table III shows the friction coefficient and the amount of transfer between two hardened nitralloy specimens run under a constant load of 1050 grams for the same distance, namely 876 inches, but at different speeds.

Table IV shows the friction coefficient and the amount transferred between two hardened, nitralloy specimens run at a relative surface speed of 73 feet per minute under a load of 1050 grams for various lengths of time, which is equivalent to various distances of travel. An autoradiograph of these runs is shown in figure 6. There seems to be a good correlation between the transfer as measured by the Geiger counter and as registered photographically.

Tables V and VI show the friction coefficient and the amount of transfer from a hardened nitralloy rider and a chromium-plated rider, respectively, to a series of rotating nitralloy specimens of different hardnesses, and the results of table V are plotted in figure 7. The softest specimens in both cases were not nitrided. All runs were made for 1 minute at 73 feet per minute under a load of 1050 grams. There was considerable scoring of the softer nitralloy surfaces by the chromium rider. The transfer is seen to be quite low.

A comparison of the transfer between hardened nitralloy and chromium plate for all the different possible combinations of the two is shown in table VII. The receiving nitralloy specimen selected had a surface hardness of 92.3 (see table V) which was the nearest to that of the rider in order to facilitate comparison of the different combinations. In all cases the chromium plate was about 0.005 inch thick and used in the as-plated condition. The runs were for 1 minute at 73 feet per minute under a load of 1050 grams.

Table VIII shows the transfer from the chromium-plated rider to the three different types of chromium-plated surfaces run for 1 minute at a speed of 73 feet per minute (with the exception of the superfinished specimen which was at 77 ft/min) and a load of 1050 grams. The transfer to the superfinished surface is seen to be quite high and the damage to both surfaces from scoring was very severe. To the chromium surface left in the as-plated condition there was also large transfer but the damage was less severe. However, there was considerable loose debris of wear particles along both sides of the track. These were wiped off before the activity count was taken. To the porous chromium plate there was least transfer and little wear of the rider, and the track was only barely visible to the eye. The friction was not measured in any of these runs.

This completes the data on the transfer to the specially prepared friction specimens. Before discussing these data the results on the transfer to the aircraft piston rings will be given.

Transfer to Piston Rings

The piston rings used were designed for use in an R-1820 aircraft engine and were supplied by the Lewis Flight Propulsion Laboratory of the NACA. They were made of both cast iron and nitrided steel, some new and some used. They are described in table IX. The used cast-iron rings were run in a cross-hatched honed nitrided steel barrel (7-10 microin.) made of Nitralloy G with a choke bore. The engine run consisted of 5 hours and 50 minutes of run-in followed by 10 hours at a brake mean effective pressure of 209 pounds per square inch and 2500 rpm. The

weight loss and unit wall pressures are given in table IX. All nitralloy
rings were made of wire-formed Nitralloy N. The used rings were run in
a cross-hatched honed nitrided steel barrel (5-8 microin.) made of
Nitralloy G with a straight bore. The engine run consisted of a 1-hour
run-in followed by 10 hours at a brake mean effective pressure of
209 pounds per square inch and 2500 rpm.

For the transfer runs the stationary specimen was the radioactive
hardened nitralloy specimen described above. All runs were made dry for
2 minutes at a rubbing speed of 73 feet per minute and a load of 1050 grams.

The next problem was to determine the amount of material transfer.
The extended geometry of the ring and the limited cone of sensitivity of
the Geiger-Müller counter would have required a long and tedious survey
of the whole ring face, followed by some kind of averaging process in
order to determine transfer by this means. Likewise the extended area
would result in too much dilution by inert base ring material if one were
to attempt to remove and concentrate the transferred material chemically.
It was therefore decided to use solely the photographic method. Using
the method described earlier in this report, one new and one used ring
were photographed at a time to insure the same film, exposure time, and
development. The exposure times were approximately 120 hours.

Some transfer was observed to all of the rings. In the case of the
nitrided rings there was no appreciable difference in the amount of
transfer to the unused and to the used rings. This was true of both
pairs of rings that were compared. A typical autoradiograph of a section
of the two tracks, one on the unused ring 126 and one on the used ring 40,
is shown in figure 8.

On the other hand, in the case of the cast-iron rings there was
definitely more transfer to the used than to the unused ring in both
cases. A print of the track on an unused ring (ring 1) and a used ring
(ring A84) is also shown in figure 8.

DISCUSSION

Since all of the transfer runs were made dry, violent chatter and
cutting or galling noises were often observed. These would set in at
varying times after the beginning of the run but were not accompanied
by marked changes in friction coefficient. This scatter in friction
values even among runs under identical conditions is seen in tables II
to VIII to range from 0.42 to 0.68 when the stationary specimen was
nitralloy and to vary between 0.76 and 0.84 when it was chromium. These
values and the degree of scatter are generally characteristic of dry

clean metal surfaces in air and the values serve as a check on the nor-
mality of the present operating conditions.

The scatter in the amounts of transfer is seen from the tables to
be even greater than that for the friction coefficient and furthermore
to bear little or no relation to the variation in the values of the
latter. It was true both for the friction specimens and the piston rings.
In the preceding investigations using the radioactive tracer method
(references 1 and 5) a similar scatter in transfer was observed but it
could have been attributed to quantitative uncertainties in the radio-
activity techniques. However, the present procedures of radioactivation
and detection were evolved largely to get around these uncertainties so
that the present scatter must be attributed to the friction process
itself. Part of its origin may be ascribed to the varying lengths of
time after the beginning of a run that pronounced scoring or galling
would set in. This in turn is presumably due to the rapidity with which
protective oxide and absorbed gas films on the surfaces are worn through.
It appears therefore that even under laboratory-controlled conditions the
durability of these films is still largely statistical and not subject to
very exact control.

A word might be said at this point about the complete lack of corre-
lation observed between the relative magnitudes of the friction and the
transfer in individual runs. Recently Whittaker (reference 11) and Bezer
and Schnurmann (reference 12) have shown that the work done in removing
material worn off in a wear test can never be more than about 1 percent
of the total frictional work done and is probably one or two orders of
magnitude less than this. (The authors have confirmed these results in
some wear measurements on drill rod.) Therefore one should not expect
that variation in that portion of the worn-off material which is trans-
ferred to the other surface could have any effect on the size of the
friction force.

Allowing, however, for this scatter, some observations can be made
from the data as regards the transfer. First, it is seen that the amount
of transfer in tables II to VIII is of the same order of magnitude as
that found in part I for transfer from nitrided nitralloy under similar
operating conditions. This is interesting in view of the rather different
methods of preparing and activating the specimens and their different
geometry. It would seem to confirm the fact that for these materials the
amount of transfer is of the order of a few micrograms for the present
conditions.

As regards dependence of transfer on individual operating conditions,
table II shows that it seems to increase with load up to about 1050 grams,
above which it remains fairly constant. With the present geometry, on
the basis of the Hertz equation, this load marks the point where the

elastic limit of the nitralloy is exceeded. Whether this coincidence is significant is not clear. The friction coefficient, within the scatter, is seen to be independent of load in agreement with Amontons' law.

In table III it is seen that the transfer for a given distance traveled seems to be independent of speed up to 73 feet per minute but is definitely less at 234 feet per minute. It might be argued that at this latter speed the rider is thrown off the track for a part of the time but this should show up in reduced friction, which it does not. It seems more probable that the high speed is more effective in knocking off weakly adhered material which had been previously deposited on the same track. This probably would not show up in the friction. The friction coefficient appears to be independent of the speed, also in agreement with the classical observations on dry friction.

The speed range investigated here is only a small fraction of that covered by a piston in a single cycle of an aircraft engine where maximum speeds of 10,000 feet per minute are often reached. Hence speeds as low as 234 feet per minute occur only in the region within 1/10 inch of top and bottom dead center. If the trend of decreasing transfer with increasing speed is continued for the higher speeds, then one should expect from table III that in an engine most of the transfer would take place at the two ends of the stroke. This would be over and above any indirect effects of speeds, such as the development of a hydrodynamic oil film, which would also tend to decrease the transfer in the middle of the stroke.

From table IV it is seen that the amount of transfer increases with the distance traveled, although somewhat less than linearly, if the allowance is made for the fact that the first run for 2628 inches may not have been typical. This generally confirms previous results (reference 5) obtained over short distances (about 3 cm).

It is of interest to compare the amount of transfer for a given distance traveled with the results obtained in part I. In that case, the load was 1000 grams, the speed was 55 feet per minute, the total distance of travel was 643 inches, and the transfer was 2.4 micrograms. This is entered in the last line of table IV for comparison and appears to be in good agreement with the other results, since, as was seen in table III, the effect of speed is negligible in this range. However, there is the significant difference that in the previous work the distance traveled was over fresh track for the whole 643 inches, whereas in the present work it was repeated many times over the same circumferential track which was only 2.36 inches long. The fourth column in table IV shows that the density of transferred material along the friction track is greatly different in the two situations. However, the fifth column shows quite good agreement for the transfer per unit distance traveled in the two cases, allowing for the difference in geometry of the samples.

Furthermore, it is seen that the weight of material transferred per inch of travel is fairly constant but decreases somewhat as the distance of travel increases. This could easily be due to successive passes of the stationary specimen over the same spot knocking or wearing off material previously transferred.

From these results it may be concluded that for these materials under a given set of conditions the amount of transfer per unit of distance traveled is fairly constant and independent of whether the travel is over fresh track or over the same track, at least up to 1000 traverses.

As regards the effect of hardness, tables V and VI and figure 7 show that the amount of transfer from both nitralloy and chromium riders decreases as the hardness of the receiving nitralloy specimen decreases. An exception appears to be the case of the chromium rider on the softest nitralloy specimen but there was unusually severe scoring in this case. The values obtained in part I for transfer to nitralloy are seen to be in good agreement with the present results. The nitralloy riders in the two cases had approximately the same hardness. It is interesting to note that the presence or absence of nitriding seems to have little effect on the transfer except as it affects the hardness even though nitriding changes the chemical composition of the surface by introducing metallic nitride constituents (reference 8). This point was ambiguous in the earlier work (part I) as it was not possible to separate the effect of nitriding from the effect of hardness per se.

From the concept of the ploughing and adhesion of metals in dry friction as outlined by Bowden, Moore, and Tabor (reference 13) transfer of metal to a surface can take place in either of two ways. These are: (1) By the ploughing of a softer material by the surface in question or (2) by the adhesion of the material to that surface. By either mechanism the transfer is generally viewed as taking place from the softer to the harder material and should increase as the hardness of the receiving surface increases relative to the other surface. In the earliest quantitative work on metal transfer, however, Sakmann, Burwell, and Irvine (reference 5) found the reverse to be true; namely, that least amount of a beryllium-copper alloy was transferred to the hardest of a series of steel riders, all the latter being harder than the copper alloy. The explanation of these results could not be found in either the ploughing or the adhesion theory, but it may have been significant that in the work the transfer to the stationary surface was measured, whereas Bowden, Moore, and Tabor discussed the transfer to the moving surface, which is also the situation in the present work.

Returning to the present results, since the hardness of the nitralloy rider lies between 85 and 90 (Rockwell 15-N), it is harder than all except one of the nitralloy receiving specimens in table V. Likewise the superficial hardness of the chromium plate is presumably harder than all those

in table VI. Thus it appears that the increase of transfer with hardness
of the receiving surfaces holds even when the transferring surface is
the harder of the two and furthermore that there is no discontinuity at
the point where the relative hardness becomes reversed. Whether the
transfer under these circumstances takes place by local adhesion of the
harder to the softer metal or by the "plucking" of particles of the
harder by the softer, as suggested by Bowden, Moore, and Tabor (refer-
ence 13), is not known. However, the present results suggest an inter-
esting extension of the theory of dry friction and particularly so as
occurring in relatively hard and nonplastic metals.

    Comparing the results in tables V and VI, it is seen that considerably
more nitralloy than chromium is transferred to a nitralloy specimen of a
given hardness. This difference might be expected both because of dis-
similarity of materials and also because of the greater surface hardness
of the chromium plate. In spite of the comparatively small transfer,
however, the chromium rider scored the softer nitralloy specimens very
badly. This, together with its performance against other chromium sur-
faces to be discussed later, suggests that the nodular protuberances on
its surface (see fig. 1) were cutting or ploughing the other softer sur-
face. Furthermore, a close examination of its surface showed that there
were isolated individual nodules which are larger and probably higher
than their neighbors, which if they happened to lie in the rubbing area
could take all of the load and act as individual cutting tools. This
may explain the relative increase in the transfer of chromium to the
softest nitralloy specimen shown in table VI.

    As regards the relative transfer between various combinations of
similar and dissimilar materials, table VII shows that, as would be
expected, the transfer was less when the two rubbing surfaces were dis-
similar than when they were the same, although the very high transfer
between the two chromium surfaces may have been due to secondary factors,
as will be discussed below. A second point of interest in table VII is
that there is significantly less transfer from stationary chromium to
moving nitralloy than for the reverse combination. This would seem
reasonable since the surface hardness of chromium plate is higher than
that of the nitralloy.

    Table VIII shows the difference in transfer behavior between
chromium-plated surfaces for different types of plate on the moving sur-
face. It evidently varies widely and this difference can probably be
ascribed to the surface geometry. The smoothest surface produced severe
chatter, and scoring set in almost immediately so that it could not be
considered satisfactory operation for any practical use. The nodular
surface was much less severely damaged but it wore the rider most severely
of the three. The porous chrome plate was by far the most satisfactory
and showed little visible wear. This performance has often been ascribed
to the surface depressions existing in this type of plate which provide

a means of escape for hard wear particles, particularly of chromium, so that they will not abrade or score the surfaces. Conversely, this would explain the poor behavior of the superfinished surface. A further factor in the bad scoring of the superfinished surface may be the cutting action of individual nodules on the surface of the rider, which has already been mentioned. This would also explain why the moving nodular surface wore the rider so badly. In a competition between two nodular surfaces it might be expected that the stationary protuberances, which have to sustain all of the rubbing, would fail before the moving ones which take the rubbing only intermittently. Once the stationary ones have failed, either by gradual wear or by breaking off, the moving ones will be able to cut deeper into the stationary worn area and particularly into the steel substrate. This point is discussed for the purpose of suggesting caution in generalizing too much the transfer results obtained from this particular chromium rider in view of its surface geometry. From this fact, and particularly the results in table VIII, it must be concluded that the transfer of chromium, as well as the wear, depends greatly on the surface geometry of the chromium plate.

Considering next the transfer to piston rings, the contrast between the two ring materials is interesting. In the case of the nitrided rings it appears that such rings did in fact always pick up small amounts of the nitralloy surface against which they were run, confirming the results found with the standard nitralloy friction specimens. This is in spite of the fact that both surfaces were extremely hard, typical of nitrided surfaces. Hence such material must be present in the formation of the coating found on used nitrided rings which was mentioned at the beginning of this report. It also appears that formation of this layer on the nitrided rings has no effect on their subsequent ability to pick up more material as shown by the track on the used ring in figure 8. Determination of this point was one of the aims of this investigation.

In the case of the cast-iron rings, the most reasonable explanation of the fact that there was more transfer to the used than to the new ring is that gradually the used ring has during the engine run picked up, by the transfer process, a very small amount of nitralloy. This material, once it has been picked up, then furnishes a base of nitralloy which behaves toward further pickup like a nitrided surface rather than a cast-iron one. This could increase the pickup in two ways. It would provide a system of two surfaces of like material running against each other which generally increases transfer (see, for instance, the results in table VII). Secondly, it would provide the cast-iron ring with a much harder surface which, as already discussed, should also increase the amount of transfer from a stationary surface of a given hardness.

A possible alternative explanation for the greater transfer to the used cast-iron ring is that the graphite in the unused ring hinders transfer but that on running this graphite is pulled out and dissipated.

This seems unlikely, however, since other workers have found evidence that running cast-iron surfaces smears the graphite over the surface (reference 14). It is more probable that the graphite becomes covered with the transferred nitralloy.

In any case it would appear from figure 6 that the running of cast-iron rings makes their susceptibility to pickup somewhat greater. This could have two effects. It could promote further pickup and possibly induce scuffing. On the other hand, it may give the cast-iron ring a very thin nitrided coating, resulting in increased wear resistance.

The universal occurrence of material transfer in all the tests made, both with the friction specimens and with the piston rings, strongly suggests that such transfer will also take place between the cylinder walls and piston rings of a running engine. This being so, it is probably present in the surface coating observed on run-in and scuffed rings which was referred to in the beginning of this report (references 2, 3, and 4). Whether it is in any way responsible for giving the coating its somewhat unique properties compared with the bulk ring material as regards wear resistance and corrosion resistance cannot be deduced from the present work. However, such an effect seems plausible, particularly in the case of nitralloy transferred to cast iron. If this is correct, it lends weight to the suggestion made in part I that a possible pretreatment of piston rings to put this desirable coating on them might consist in running them in a special cylinder having walls of selected composition and controlled hardness.

SUMMARY OF RESULTS

From results of tests to determine what role, if any, is played by the transfer of metal from one rubbing surface to the other in the formation of the characteristic surface coatings on certain piston-ring materials during run-in in an aircraft engine (including results from NACA TN 1355 where comparison is valid), the following statements may be made:

1. In the case of all the combinations of materials studied there was a definitely observable amount of transfer. These materials were nitralloy, both nitrided and unnitrided, various types of chromium plate, and piston-ring cast iron. This shows that the phenomenon of material transfer which had been previously demonstrated by several groups of workers to take place in the case of soft metals also takes place in the case of some of the hardest technical metals and alloys.

2. From a given stationary surface the transfer to a moving surface decreased as the hardness of the latter decreased. This was true even when it was less hard than the stationary surface.

3. The amount of transfer was found to be roughly proportional to the distance traveled by the stationary specimen and this was independent of whether this travel was repeated many times over the same track on the moving surface or was continually over fresh surface. The vibration became somewhat less than linear at the longest distances of travel.

4. The amount of transfer for a given distance of travel was constant over a range of low speeds but began to decrease at higher speeds.

5. Between nitralloy and chromium-plated surfaces, more material is transferred from nitralloy to chromium than vice versa.

6. In the case of chromium plate at least, the amount of transfer as well as the degree of scoring and wear depended greatly on the surface geometry of the plate.

7. Appreciable transfer took place to both nitrided-steel and cast-iron piston rings which had already been run in an aircraft engine having nitrided-steel barrels. Furthermore, by comparison with the transfer to similar unused rings, it appears that whatever layer is formed on such rings during running did not hinder further metal pickup and in the case of the cast-iron rings it actually increased the pickup.

CONCLUDING REMARKS

From the study of metal transfer between sliding surfaces, it seems likely that under the conditions of running in an aircraft-engine cylinder a certain amount of nitrided steel from the barrel will be transferred to the surfaces of nitrided-steel, cast-iron, or chromium-plated rings. Such transferred material may, therefore, be a factor in the formation of the characteristic surface layer often observed on such rings.

Massachusetts Institute of Technology
      Cambridge, Mass., August 1, 1948

REFERENCES

1. Sakmann, B. W., Grossman, N., and Irvine, John W., Jr.: A Study of Metal Transfer between Sliding Surfaces. NACA TN 1355, 1947.

2. Bobrowsky, A. R., Kittel, J. Howard, and Boegli, Charles P.: Experimental Study of the Coating Formed on Nitrided-Steel Piston Rings during Operation in Nitrided-Steel Cylinders. NACA ACR 4C31, 1944.

3. Good, J. N., and Brockway, L. O.: An Electron and X-Ray Diffraction Investigation of Surface Changes on Nitrided-Steel Piston Rings during Engine Operation in Nitrided-Steel Cylinder Barrels. NACA ACR E4L27, 1945.

4. Clark, Thomas P., and Vierthaler, Walter A.: An Electron-Microscope Study of Used Nitrided-Steel Piston Rings. NACA TN 1132, 1946.

5. Sakmann, B. W., Burwell, J. T., Jr., and Irvine, J. W., Jr.: Measurements of the Adhesion Component in Friction by Means of Radioactive Indicators. Jour. Appl. Phys., vol. 15, no. 6, June 1944, pp. 459-473.

6. Peacock, W. C., et al.: The Use of Two Radioactive Isotopes of Iron in Tracer Studies of Erythrocytes. Jour. Clinical Investigation, vol. 25, no. 4, July 1946, pp. 605-615.

7. Bradt, H., et al.: Die Radioaktive Umwandlung des Cr^{51}. Helvetica Physica Acta, vol. 18, 1945, pp. 259-260.

8. Floe, C. F.: The Nitriding of Steel. Metal Progress, vol. 50, 1946, p. 1212.

9. Brenner, Abner, Burkhead, Polly, and Jennings, Charles: Physical Properties of Electrodeposited Chromium. Res. Paper RP1854, Jour. Res., Nat. Bur. Standards, vol. 40, no. 1, Jan. 1948, pp. 31-59.

10. Gregory, J. M.: Radioactive Tracers in the Study of Friction and Lubrication. Nature, vol. 157, no. 3988, April 6, 1946, pp. 443-444.

11. Whittaker, E. J. W.: Friction and Wear. Nature, vol. 159, no. 4042, April 19, 1947, p. 541.

12. Bezer, H. J., and Schnurmann, R.: The Rate of Wear in the Region of the Validity of Amonton's Law. Nature, vol. 161, May 8, 1948, p. 728.

13. Bowden, F. Philip, Moore, A. J. W., and Tabor, D.: The Ploughing and
        Adhesion of Sliding metals. Jour. Appl. Phys., vol. 14, no. 2,
        Feb. 1943, pp. 80-91.

14. Finch, G. I., Quarrell, A. G., and Wilman, H.: Electron Diffraction
        and Surface Structure. Trans. Faraday Soc., vol. XXXI, pt. 9,
        no. 172, Sept. 1935.

TABLE I

SURFACE HARDNESS AND SURFACE ROUGHNESS OF FRICTION SPECIMENS

Material	Type of surface	Roughness (rms microin.)	Hardness (Rockwell 15-N)
Nitralloy	Ground	19	92.3
Do------------	-----do------	------	90.0
Do[a]-----------	-----do------	------	85-90 (approx.)
Do------------	-----do------	15	81.0
Do------------	-----do------	------	77.4
Do(tempered[b])-	-----do------	28	76.3
Do(unnitrided)	-----do------	------	68.5
Do------------	-----do------	------	67.8
Chromium plate	Nodular	24	94
Do------------	Superfinished	1	94
Do------------	Porous	5-10[c]	---------------
Do(studs)------	Nodular	20-40	94

[a]Radioactivated.
[b]Nitrided and then tempered for 8 hr. at 1325° F.
[c]Roughness of plateaus as estimated from a Brush Analyzer trace.

TABLE II

EFFECT OF APPLIED LOAD ON TRANSFER

Load (grams)	Friction coefficient	Amount of material transferred (micrograms)
315	0.42	3.5
315	.45	2.8
1050	.60	5.4
1050	.42	5.7
3150	.59	5.3
4870	----	5.3

TABLE III

EFFECT OF SPEED ON TRANSFER

Speed (ft/min)	Friction coefficient	Amount of material transferred (micrograms)	Average
8	0.54	2.4	2.5
8	.53	2.6	
73	.58	2.7	2.6
73	.56	2.4	
234	.51	.7	.7
234	.56	.7	

TABLE IV

EFFECT OF DISTANCE OF TRAVEL ON TRANSFER

Distance of travel (in.)	Friction coefficient	Amount of material transferred		
		Total weight (micrograms)	Weight per unit length of track (micrograms/in.)	Weight per unit distance of travel (microgram/in.)
88	0.54	1.0	0.42	0.0114
88	.50	--------	------	------
292	.62	1.8	.76	.0062
292	.59	1.9	.80	.0065
876	.60	5.4	2.3	.0062
876	.42	5.7	2.4	.0065
2628	.68	3.4 (?)	1.4 (?)	.0013 (?)
2628	.56	10.6	4.5	.0040
From part I: 643	----	2.4	.0037	.0037

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TABLE V

EFFECT OF HARDNESS ON TRANSFER FROM NITRALLOY

Hardness (Rockwell 15-N)	Friction coefficient	Amount of material transferred (micrograms)	
			Average
92.3	0.59	5.4	5.6
92.3	.42	5.7	
81.0	.58	2.7	2.6
81.0	.56	2.4	
76.3 (tempered)	----	.8	1.1
76.3 (tempered)	.48	1.4	
67.8 (unnitrided)	----	.8	.6
67.8	----	.5	
From part I:			
86.0	----		[a]3.3
74.5 (unnitrided)	----		[a]1.0

[a]Corrected to distance of travel of 876 in.

TABLE VI

EFFECT OF HARDNESS ON TRANSFER FROM CHROMIUM

Hardness (Rockwell 15-N)	Friction coefficient	Amount of material transferred (micrograms)	
			Average
90.0	0.79	0.77	0.71
Do---------------	----	.54	
Do---------------	----	.82	
77.4	.76	.38	.35
Do---------------	----	.25	
Do---------------	----	.43	
68.5 (unnitrided)	.84	.95	.92
Do---------------	----	.77	
Do---------------	----	1.04	

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TABLE VII

TRANSFER BETWEEN NITRALLOY AND CHROMIUM PLATE

Transfer to –	Amount of material transferred from – (micrograms)			
	Nitralloy		Chromium	
		Average		Average
Nitralloy Do---------------- Do----------------	5.4 5.7	5.6	0.77 .54 .82	0.71
Chromium Do---------------- Do---------------- Do(from part I)[a]--	2.1 2.9 3.4	2.8 2.9	12.8 17.3 12.0	14.0

[a]Corrected to distance of travel of 876 in.; also chromium plate was only 0.001 in. thick.

TABLE VIII

TRANSFER TO VARIOUS TYPES OF CHROMIUM PLATE

Type of surface	Amount of material transferred (micrograms)		Remarks
		Average	
Superfinished Do---------------- Do---------------- Do----------------	5.1 16.8 3.3 16.6	10.5	Track badly scored
As plated (nodular) Do---------------- Do----------------	12.8 17.3 12.0	14.0	Rider badly worn; track relatively unscored
Porous chromium plate Porous chromium plate	0.2 1.4	0.8	Track barely visible; rider not worn

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TABLE IX

PISTON RINGS USED FOR RADIOACTIVE TRANSFER

Identi-fication number	Material	Hardness (Rockwell 15-N)	Ring	Engine-run data			Friction coefficient
				Weight loss (gram)	Unit wall pressure (lb/sq in.)		
					Initial	Final	
1	Cast iron	--	Unused	-----	----	----	0.25
2	Cast iron	--	Unused	-----	----	----	.18
A83	Cast iron	--	Top compression	0.039	44.7	8.8	.18
A84	Cast iron	--	Second compression	.013	59.6	31.9	.38
117	Nitrided	89	Unused	-----	----	----	.45
126	Nitrided	87	Unused	-----	----	----	.61
39	Nitrided	90	Top compression	.030	15.7	14.1	.56
40	Nitrided	89	Second compression	.017	15.5	14.5	.32

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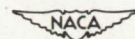
Figure 1.- Photomicrograph of thick chromium plate (about 0.005 in.) in as-plated condition, X100.
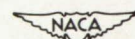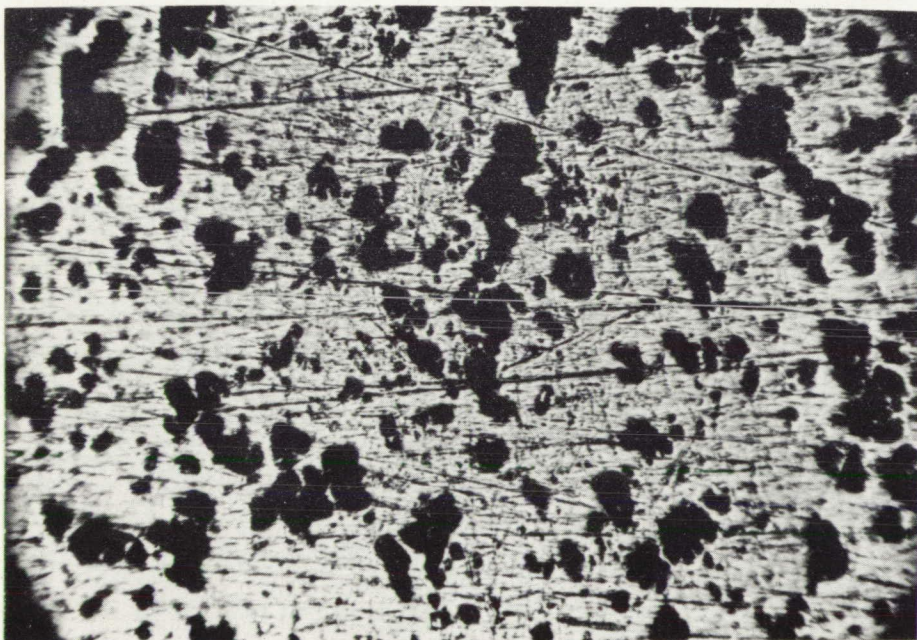
Figure 2.- Photomicrograph of porous chromium plate, X100.

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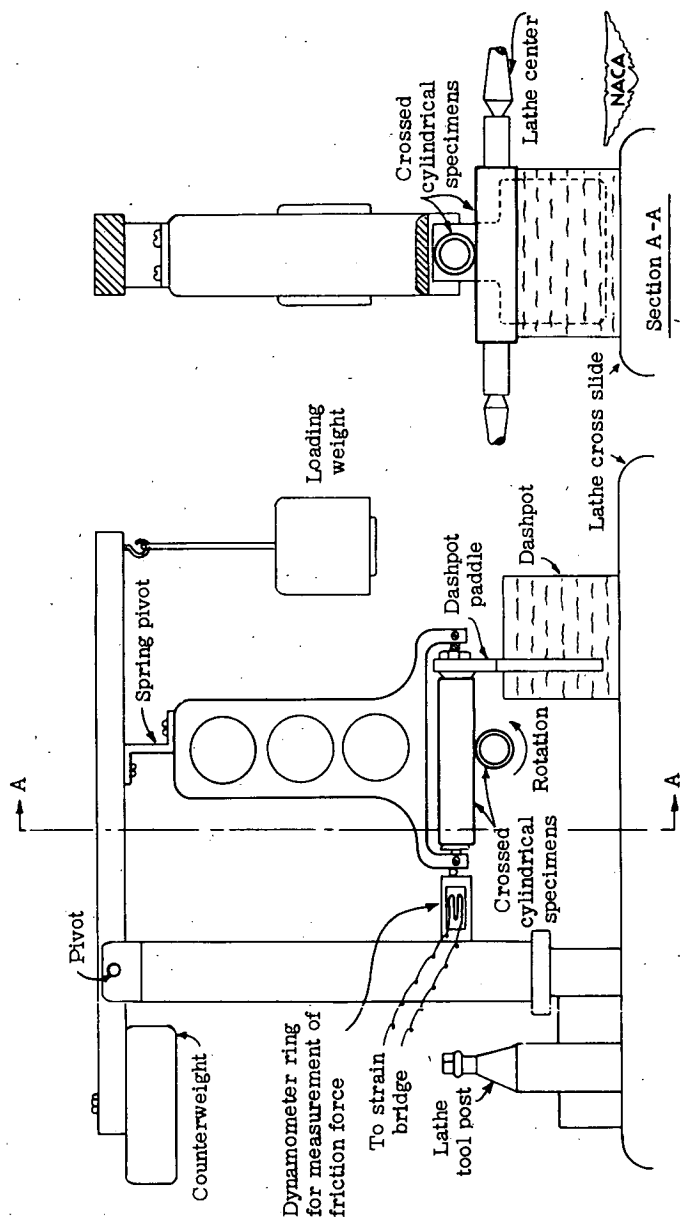
Figure 3.- Lathe-mounted friction apparatus.
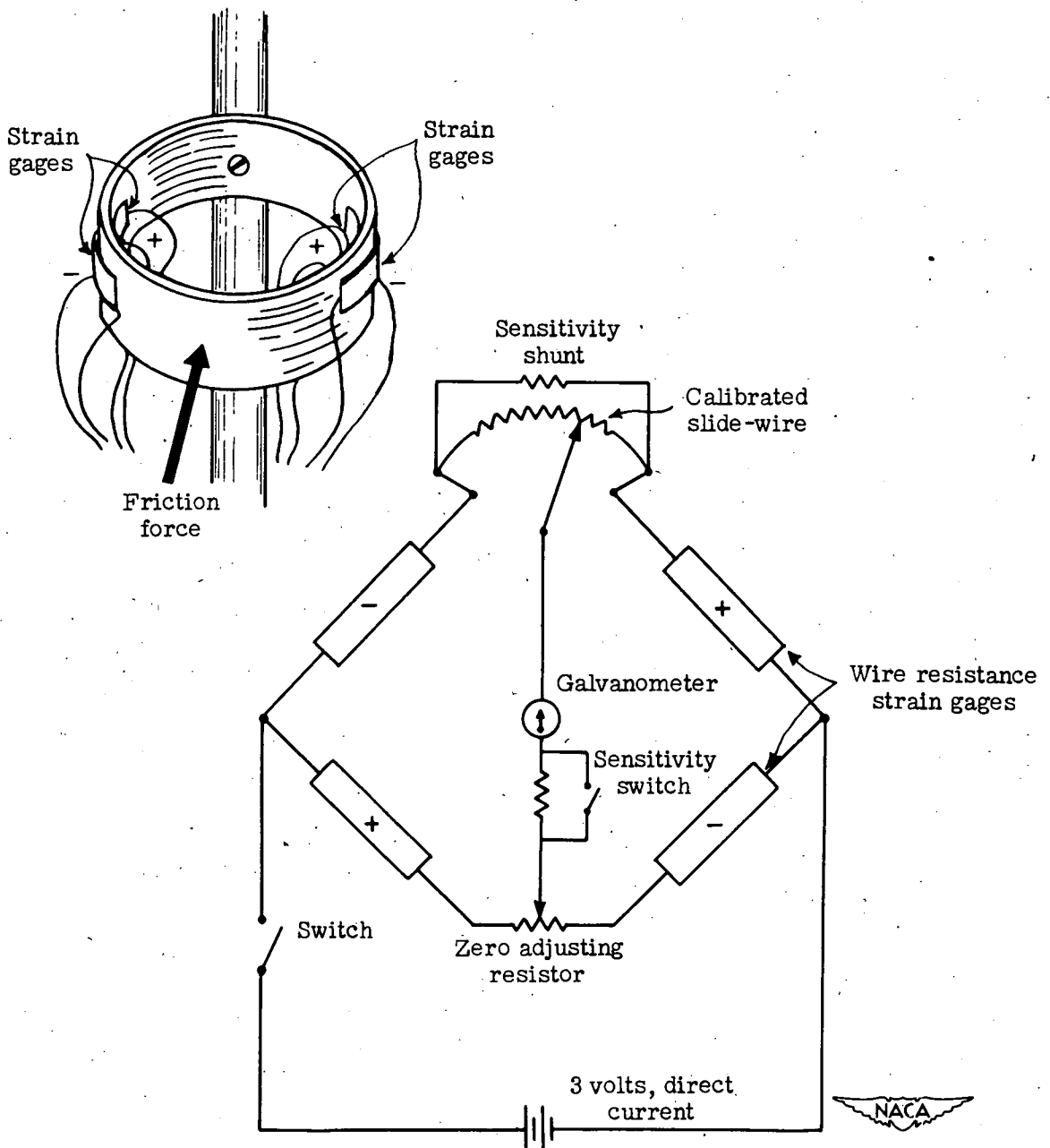
Figure 4.- Schematic diagram of friction-force measuring circuit. Plus and
    minus signs indicate that strain gages are in compression and tension,
    respectively.
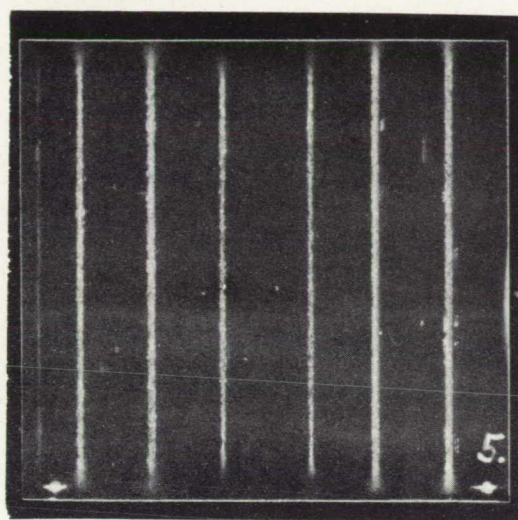
Figure 5.- Autoradiograph of friction tracks of nitralloy run against nitralloy
for a distance of 876 feet at a speed of 73 feet per minute under various
loads. Tracks a and b, 1050 grams; c and d, 315 grams; e, 4870 grams;
f, 3150 grams.
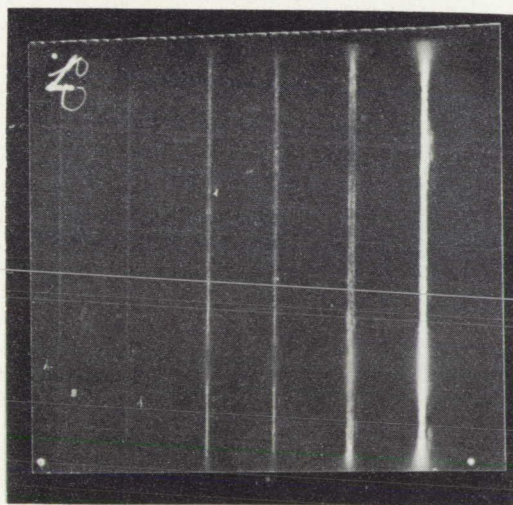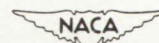
Figure 6.- Autoradiograph of friction tracks of nitralloy run against nitralloy
at a speed of 73 feet per minute under a load of 1050 grams for various
distances of travel. Tracks a and b, 88 inches; c and d, 292 inches;
e and f, 2628 inches.

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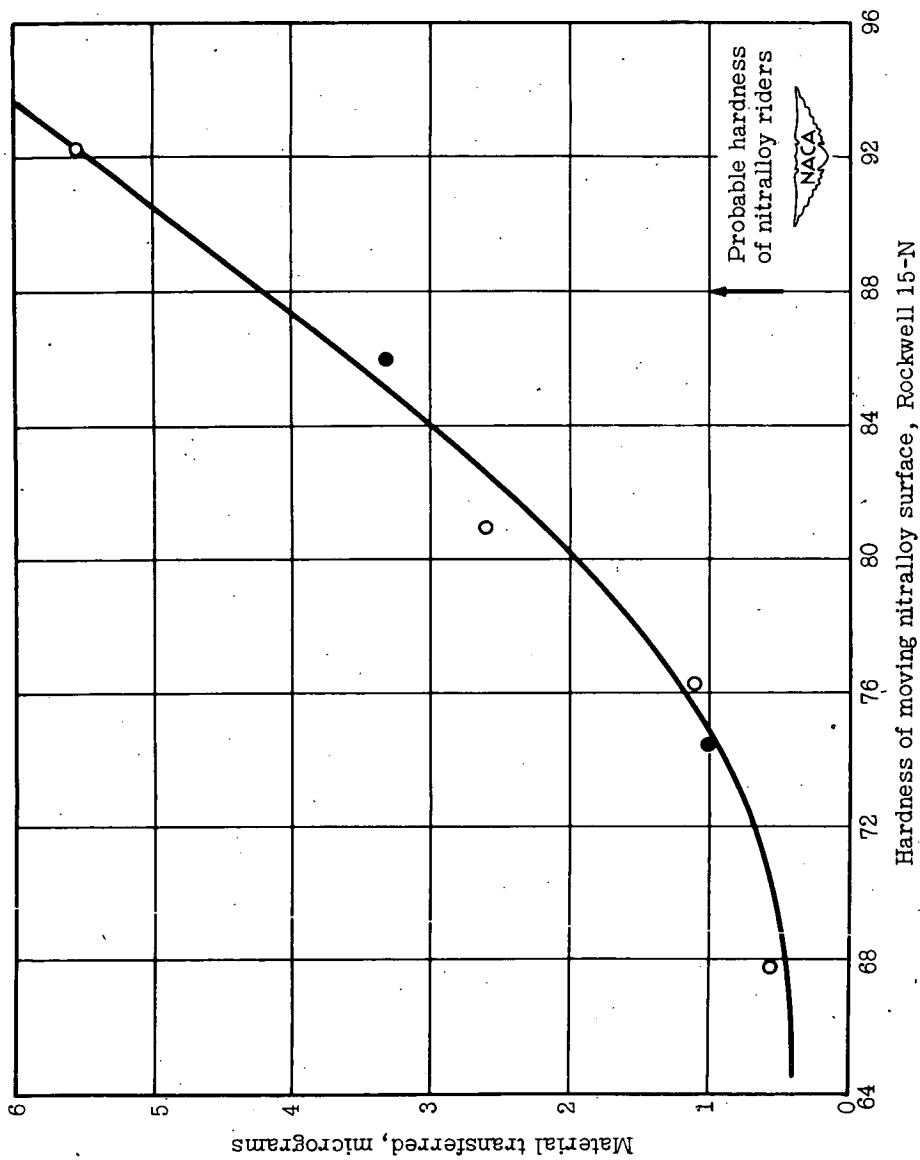
Figure 7.- Material transferred from nitralloy riders to a series of moving nitralloy surfaces of varying hardness for a distance of 876 inches at a speed of 73 feet per minute and a load of 1050 grams. Filled-in circles are data from part I.

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(a) Nitrided piston rings.
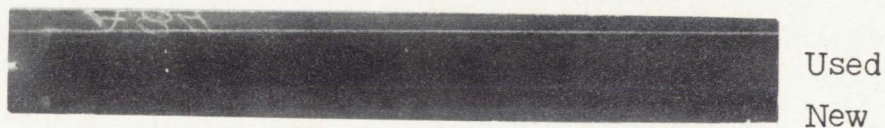
(b) Cast-iron piston rings.
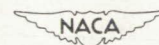
Figure 8.- Autoradiographs of material transferred from nitralloy to new and used nitrided and cast-iron piston rings.

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Abstract

Continuation of research reported in NACA TN 1355 to determine what role, if any, is played by the transfer of metal from one rubbing surface to the other in the formation of characteristic surface coatings on certain piston-ring materials during run-in in an aircraft engine. The technique consists of making one of the two rubbing surfaces radioactive, carrying out the friction test, and then examining the other surface for signs of radioactivity. Materials examined were nitrided and unnitrided nitralloy steel and chromium-plated surfaces. Transfer to actual piston rings, both new and used, was investigated. Effects on transfer of load, speed, distance of travel, repeated travel over the same path, hardness of the moving surface, and type of chromium plate were studied.

NACA TN 2271

Further Study of Metal Transfer between Sliding
Surfaces.

By J. T. Burwell and C. D. Strang

NACA TN 2271
January 1951

(Abstract on Reverse Side)

Burwell, J. T., and Strang, C. D.